

Progress in observing and modelling the urban boundary layer

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Published Version

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Barlow, J. F. (2014) Progress in observing and modelling the urban boundary layer. *Urban Climate*, 10 (2). pp. 216-240.

ISSN 2212-0955 doi:

<https://doi.org/10.1016/j.uclim.2014.03.011> Available at

<https://centaur.reading.ac.uk/38573/>

It is advisable to refer to the publisher's version if you intend to cite from the work. See [Guidance on citing](#).

Published version at: <http://dx.doi.org/10.1016/j.uclim.2014.03.011>

To link to this article DOI: <http://dx.doi.org/10.1016/j.uclim.2014.03.011>

Publisher: Elsevier

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Urban Climate

journal homepage: www.elsevier.com/locate/uclim

Progress in observing and modelling the urban boundary layer

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ARTICLE INFO

Article history:

Received 26 September 2013

Revised 20 March 2014

Accepted 28 March 2014

Available online xxxx

Keywords:

Urban

Urban surface energy balance

Boundary layer

Roughness sub-layer

Surface heterogeneity

Mesoscale circulations

ABSTRACT

The urban boundary layer (UBL) is the part of the atmosphere in which most of the planet's population now lives, and is one of the most complex and least understood microclimates. Given potential climate change impacts and the requirement to develop cities sustainably, the need for sound modelling and observational tools becomes pressing. This review paper considers progress made in studies of the UBL in terms of a conceptual framework spanning microscale to mesoscale determinants of UBL structure and evolution. Considerable progress in observing and modelling the urban surface energy balance has been made. The urban roughness sub-layer is an important region requiring attention as assumptions about atmospheric turbulence break down in this layer and it may dominate coupling of the surface to the UBL due to its considerable depth. The upper 90% of the UBL (mixed and residual layers) remains under-researched but new remote sensing methods and high resolution modelling tools now permit rapid progress. Surface heterogeneity dominates from neighbourhood to regional scales and should be more strongly considered in future studies. Specific research priorities include humidity within the UBL, high-rise urban canopies and the development of long-term, spatially extensive measurement networks coupled strongly to model development.

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1. Introduction

The urban boundary layer is the part of the atmosphere in which most of us on the planet now live, and is one of the most complex and least understood microclimates. As urbanization proceeds ever more quickly, the need for accurate weather forecasting at the urban scale becomes critical, and longer term studies of urban microclimate become more important for health and well-being as cities become larger, hotter and more polluted. In the face of climate change, sustainable design and planning of our cities is essential and a sound understanding of the microclimate must play a role in planned changes such as increasing green infrastructure and densification.

Whilst the best known urban climate phenomenon is the urban heat island (UHI), observed at the surface, the processes controlling it act at a range of spatial and temporal scales spanning the depth of the urban boundary layer (UBL). Further progress in simulating thermal comfort, air quality and city ventilation depends on accurate observations and modelling of UBL processes. This review paper considers the progress made in studies of the UBL. Firstly, a brief history of key research milestones is outlined. Then a conceptual framework is described to provide definition of the various layers and scales relevant to the UBL. There follows a systematic review of research into the UBL starting from the microscale up to the regional scale. Conclusions are drawn as to what the research priorities are for the future, particularly for theoretical development as a sound basis for operational models.

2. Development of observational and modelling techniques

There have been various milestones in studies of the urban boundary layer as shown in Table 1. Key points in the study of rural boundary layers are also shown for reference. Progress in terms of observational and modelling techniques are briefly discussed, but the reader is also referred to the excellent reviews of Grimmond (2005) and Martilli (2007), following plenary lectures at the International Conference for Urban Climate (ICUC) held in 2003 and 2006, respectively. For extensive, general information on urban modelling, see also Baklanov et al. (2009), and for a focus on dispersion, see the review by Britter and Hanna (2003).

2.1. Observations

One of the first experiments involving study of the UBL was the Urban Air Pollution Dynamic Research Network in New York in the 1960s (Davidson, 1967; Bornstein, 1968). Using helicopter-based temperature measurements, pilot balloons and some of the first numerical modelling, an investigation was made into the spatial extent of the UHI with height, essentially the UBL structure. The Metropolitan Meteorological Experiment (METROMEX – Changnon et al., 1971; Changnon, 1981) was another major US campaign in the early 1970s that had more of a focus on the hydrological cycle, considering urban-induced moisture convergence and the impact on rain formation. More sophisticated instrumentation was used, including rain radars and aircraft flights. Later, RAPS (Schiermeier, 1978) took place in the same city, this time focusing on air pollution. An important US-based review of progress occurred in 1983 at a conference in Baltimore. The resulting monograph (Kramer, 1987) raised a sophisticated range of questions that are still not answered today, about advection and vertical profiles. During the same period, the classic US Kansas and Minnesota experiments were taking place to investigate, respectively, the turbulent surface and mixed layers of the rural boundary layer. These definitive experiments formed the basis of our understanding of land-based rural boundary layers, and their results provide a benchmark to which UBL results can be compared (see Sections 4.3 and 4.4).

Internationally, air quality has been the most common motivation for observing the UBL. IMADA-AVER (Doran et al., 1998) was an important study into Mexico City's UBL: lying within a mountain basin, its pollution episodes are infamous and several wind profilers complemented regular radiosonde and rawinsonde releases in investigating mean wind, temperature and humidity structure. ESQUIF in Paris (Menut et al., 2000) was a major collaboration involving extensive UBL and air pollution measurements, as well as development of mesoscale air quality modelling techniques. A COST Action is a European Union scheme for promoting co-operation in science across all European coun-

Table 1

A brief history of urban boundary layer research, including key milestones.

Year	Milestone	Key Refs.	Comment
1966	Urban Air Pollution Dynamic Research Network (New York)	Davidson (1967), Bornstein (1968)	Bornstein (1968) investigation of UBL temperature structure by helicopter
1968	Kansas Experiment	Kaimal et al. (1972)	Established MOST theory predictions for rural surface layer
1970	Numerical simulation of UHI circulations	Delage and Taylor (1970)	One of first simulations of city-induced thermal circulations
1971–1976	METROMEX, St Louis, US	Changnon (1981)	Focus on hydrological cycle
1973–1977	Regional Air Pollution Study (RAPS), St Louis	Schiermeier (1978)	Focus on air quality
1973	Minnesota Experiment	Kaimal et al. (1976)	First experimental investigation into ABL mixed layer scaling
1974	Lab simulation CBL	Willis and Deardorff (1974)	First lab experiment to establish CBL mixed layer scaling
1978	Beijing Tower erected (325 m), China	Yu et al. (2013)	Tower initially on edge of city, now in centre, records on-going urbanization impacts on UBL
1983	Modelling the UBL Conference, Baltimore	Kramer (1987)	Definitive description of UBL as known at the time, including pollutant dispersion
1997	IMADA-AVER UBL experiment, Mexico City	Doran et al. (1998)	One of first major experiments outside US and Europe with extensive use of remote sensing
1998–1999	ESQUIF: air pollution over Paris	Menut et al. (2000)	First major European study of megacity air pollution, including UBL and chemistry, modelling and measurements
1999–2004	COST Action 715	Fisher et al. (2006), Rotach et al. (2005)	Comprehensive synthesis of European UBL studies, including BUBBLE campaign of 2001–2002 in Basel
2009–2011	International urban surface scheme comparison project	Grimmond et al. (2010)	Comparison of numerous urban surface parameterizations with observed flux data in staged experiment

tries. COST Action 715 (Meteorology Applied to Air Pollution Problems) took place from 1999 to 2004 and investigated basic properties of the UBL. The BUBBLE field campaign inspired by the Action (Rotach et al., 2005) yielded perhaps the most definitive field study of the urban roughness sublayer (RSL) to date (Christen, 2005) and new parameterizations of canopy turbulence for dispersion modelling (Kastner-Klein and Rotach, 2004). Another intriguing and ongoing UBL experiment consists of the Beijing Tower, 325 m high and built in 1978 on the outskirts of Beijing, China but now very much at the heart of a megacity. Although observations are not continuous, the meteorological profiles measured over 30 years are a fascinating insight into the effect of rapid urbanization on the UBL (Yu et al., 2013).

2.2. Development of theory and models

Early 2-D simulations of the UBL were performed with mesoscale models, such as the pioneering URBMET model (Bornstein, 1975), and were able to capture the broad thermal circulations generated by the urban heat island (UHI). As computing power has increased, urban parameterizations have become more physically realistic (Martilli, 2007) with an explosion of development occurring particularly since 2000. This has been driven in part by increasing resolution of operational weather forecast models and the recognition of the importance of accurate UBL simulation for air quality forecasting. Numerous urban surface schemes of varying complexity have been developed, which led recently to the first international comparison (Grimmond et al., 2010, 2011). With increasing development of remote sensing techniques that can measure beyond the microscale, evaluation of mesoscale models becomes easier. However, a fundamental property of Numerical Weather Prediction (NWP) model output is that it represents an ensemble-averaged boundary layer, whereas individual measurements

are but a single realisation (Martilli, 2007). It was also observed during the COST 715 action that a general theoretical basis for the UBL is still lacking, and that NWP models provide a largely unvalidated, “best guess” of the physical processes. The trend towards much longer observational campaigns and urban testbeds (Koskinen et al., 2011) provides much more robust data with which to test models.

The vast majority of urban Computational Fluid Dynamics (CFD) modelling has been done at the scale of single buildings or neighbourhoods with domains less than 1 km in extent, for the purpose of dispersion (Tominaga and Stathopoulos, 2013; Belcher et al., 2012) or wind engineering (Blocken et al., 2013). Studies of fundamental properties of urban canopy turbulence have been done for idealised arrays, such as 2-D street canyons or cavities (Li et al., 2006), or 3-D cuboid arrays (Coceal et al., 2006; Xie et al., 2008). Validation against wind tunnel data has shown that numerical approaches permitting unsteady flow (e.g., Large Eddy Simulation (LES), Direct Numerical Simulation (DNS), Unsteady Reynolds-Averaged Navier-Stokes (URANS)) perform better in reproducing mean flow patterns than RANS (Tominaga and Stathopoulos, 2013). Correct representation of atmospheric scales of turbulence in the inflow is important (Li et al., 2006; Tominaga and Stathopoulos, 2013), and the correct reproduction of buoyant flows depends critically on the lower boundary conditions for heat fluxes and temperature at building walls, as well as near-wall resolution (Boppana et al., 2012). There have been few attempts to model traffic-induced turbulence (Di Sabatino et al., 2003; Jicha et al., 2000) and very little work on modelling urban trees (Gromke et al., 2008), despite the ubiquity and impact of these roughness elements on urban flow. Given the computational cost, there have been few studies with a domain large enough to capture convective scale eddies as well as resolving urban canopy turbulence (Castillo et al., 2011). Instead, several authors have coupled mesoscale to CFD models, with varying methods of coupling (Mochida et al., 2011; Martilli, 2007). As CFD domains increase (e.g., UBL depth of 1 km at 5 m resolution) and NWP grid box size decreases (e.g., to 100 m), interesting research lies ahead as the scale of modelling tools pushes the validity of existing parameterizations. High quality validation data at full-scale will be an essential part of such developments (Belcher et al., 2012; Tominaga and Stathopoulos, 2013), alongside physical modelling data.

3. Conceptual framework for the urban boundary layer

Before discussion of the key results from UBL research, a framework for describing the urban boundary layer is now outlined to aid discussion. The UBL consists of the following characteristics some of which are depicted schematically in Figs. 1 and 2:

- (1) Horizontal scales can be defined: street (of order 10–100 m), neighbourhood (100–1000 m) and city (10–20 km) – see Figs. 1 and 2. These can be interpreted as scales on which the urban morphology becomes homogeneous (i.e., a single house or street; a collection of buildings of similar height and shape in a neighbourhood; a town or city which is rougher than the surrounding rural area).
- (2) The urban surface energy balance is distinct from a rural one as generally (a) sensible heat flux is higher due to the man-made materials and increased surface area, (b) latent heat flux is lower due to a lower fraction of vegetative land-use cover, (c) urban surfaces have higher thermal inertia due to high heat capacity of the man-made surfaces, leading to a non-negligible storage flux, (d) complex processes of shadowing and multiple reflections affect short-wave radiation fluxes, and the wide range of materials affect the emissivity and thus long-wave fluxes, resulting (surprisingly) in little difference in net radiation flux, and (e) anthropogenic heat sources act in addition to the solar-driven energy balance, effectively increasing the sensible heat flux. The urban surface energy balance drives not only the temporal evolution of the urban heat island (UHI), but also the evolution and vertical structure of the UBL.
- (3) Roughness elements are large, and exert significant drag on the flow. An urban roughness sub-layer (RSL) can be defined of depth between $2-5H$, where H is the mean building height. Within this layer, flow is highly spatially dependent (see Fig. 2); turbulence can dominate the mean flow; and turbulence has different characteristics from the flow in the inertial sub-layer (ISL) above, where the turbulence is homogeneous and fluxes vary little with height. The urban canopy layer is defined as the layer up to mean roof height.

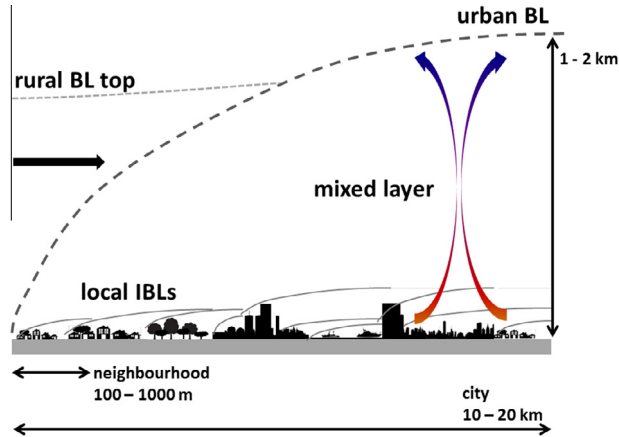


Fig. 1. Schematic diagram of daytime convective urban boundary layer with wind flowing from left to right. Dashed lines indicate top of rural and urban boundary layers; solid lines indicate local internal boundary layers. Approximate order of magnitude is given by, e.g., 100–1000 m. Note the exaggeration of the vertical scale.

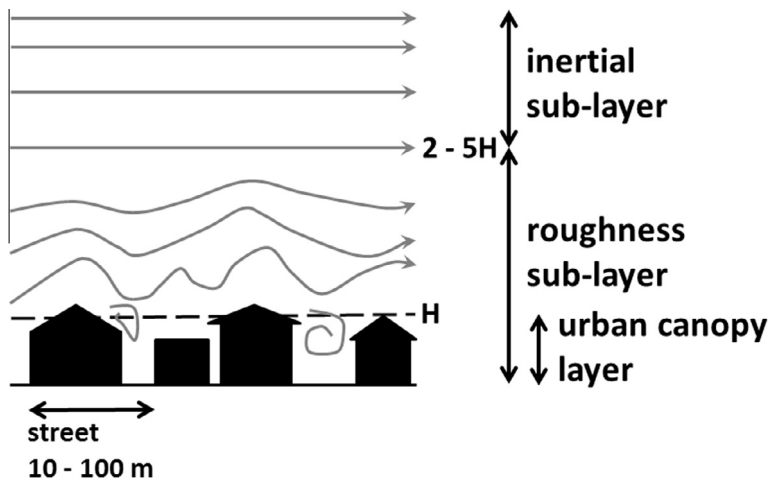


Fig. 2. Schematic diagram of roughness and inertial sub-layers. Grey arrows indicate streamlines. Dashed line indicates mean building height H .

- (4) Urban surfaces are heterogeneous and thus horizontal advection of heat, momentum, etc. is a key flow characteristic at both city and neighbourhood scale. At city scale an Internal Boundary Layer (IBL) forms at the interface between the smoother rural and rougher urban surfaces (see Fig. 1). If the city is large enough, the urban IBL fully replaces the rural boundary layer upstream (i.e., attains the upstream boundary layer depth). On a neighbourhood scale, flow is continually adjusting to changes in roughness (i.e., from parks to suburbs to city centre), producing local IBLs where flow is locally in equilibrium with the underlying surface. The IBL depth to fetch ratio is approximately 1:10, whereas the equilibrium layer to fetch ratio is approximately 1:100 (e.g., Wieringa, 1993, as quoted in Roth, 2000). Equilibrium layer is here defined as being where the mean flow and momentum flux profiles are consistent with the surface roughness and it occupies the lowest 10% of IBL depth – the remaining 90% of the IBL is a transition layer where profiles and fluxes adjust gradually back to the undisturbed profiles above. Multiple

changes of roughness lead to complex three-dimensional structure of the lower part of the UBL due to overlapping neighbourhood-scale IBLs. In this case, a blending height can be defined, above which fluxes and profiles are spatially homogeneous (see Section 4.5). Some authors use this term to define the top of the RSL – this is not done in this paper so that the term is used in accordance with other “non-urban” literature on surface heterogeneity (e.g., Mason, 1988; Mahrt, 2000).

- (5) Above the top of the ISL or blending height (whichever is higher) it is assumed that the UBL adopts a classical atmospheric boundary layer structure – in convective conditions there is a mixed layer (see Fig. 1), whilst at night-time there is a residual layer above a ground-based stable layer. Many observations of the urban surface energy balance demonstrate a small, positive sensible heat flux at night which drives a nocturnal mixed layer consisting of a shallow convective or near-neutral layer of turbulence. Above this layer it is assumed that there is a weakly stable residual layer.
- (6) The UBL structure is determined not only by urban surface characteristics but also by mesoscale thermal circulations, mesoscale referring to a scale of 10–100 km. By day and with weak synoptic forcing (i.e., low wind, sunny conditions) buoyant up-draughts over the hotter urban surface can induce an urban thermal circulation. Coastal cities are subject to sea/land breezes due to regional scale land–sea temperature contrasts. The urban thermal circulation may even enhance the sea breeze due to stronger updraughts over the warmer urban surface. Similarly, cities in hilly/mountainous terrain may experience up-slope (anabatic) flow due to solar heating of the slopes, and down-slope (katabatic) flow due to density currents at night. In flat terrain at night, a regional scale Low Level Jet (LLJ) may be generated due to the stable rural surface layer and may interact with the nocturnal UBL. In all cases except for the urban thermal circulation, the urban area does not drive the flow, and the UBL structure will be modified due to processes acting not at city but at regional scale.

4. Current state of knowledge

Having defined the key elements and scales of the urban boundary layer, the next sections review progress across a range of methodologies in developing tools necessary for UBL research, and basic research findings. At the end of each sub-section, a summary will be given including recommendations for further research.

4.1. Surface energy balance

Urban boundary layer flow characteristics arise in response to exchange of momentum and energy with the urban surface, which is clearly distinct from natural surfaces in form and material characteristics. The excellent review of Arnfield (2003) gives a comprehensive overview of the urban surface energy balance (USEB) from building scale up to city scale and its role in producing the urban heat island. The USEB for a given volume encompassing the urban canopy (Arnfield, 2003) is given by

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \quad (1)$$

where Q^* is the net radiation, Q_F is the anthropogenic heat flux, Q_H is the sensible heat flux, Q_E is the latent heat flux, ΔQ_S is the storage heat flux, and ΔQ_A is the advective heat flux (where “flux” is used as short-hand for the more technically correct “flux density”). In this section, focus is put on current ability to observe and model the impact of the USEB on UBL flow structure.

4.1.1. Urban surface energy balance models

In terms of representation of urban surface energy balance in mesoscale models there has been an explosion of development over the last decade (Masson, 2000; Martilli et al., 2002; Martilli, 2007; Baklanov et al., 2009). This has been driven in part by the need to urbanize operational numerical weather prediction models as urban areas are better resolved, and was first done in the UK Met Office weather forecast model by Best (2005). The recent International Urban Energy Balance Comparison Project (Grimmond et al., 2010, 2011) was a huge collective effort to compare modelled fluxes using

32 different surface schemes with high quality observations. No single model had the best performance across all fluxes, and the results were highly sensitive to the quality of the input data (e.g., thermal characteristics of urban materials, morphology of buildings), which is often hard to achieve. The importance of accurate representation of vegetation was highlighted in simulating correct partitioning of the turbulent fluxes. This is especially important for simulating UBL dynamics, as growth rate and depth of the UBL is determined primarily by the sensible heat flux.

4.1.2. Urban surface energy balance observations

There has been much development in the methodology of urban flux measurement, i.e., choosing sites in neighbourhoods with sufficient fetch for the height of measurement to be within the inertial sub-layer (Roth, 2000; Oke, 2004). Consequently a growing number of measurements constitute the Urban Flux Network¹ that is maintained by the International Association for Urban Climate. Such sites increasingly have long-term aims such as evaluation of carbon dioxide fluxes for net ecosystem exchange estimates or air quality emissions estimates (e.g., Langford et al., 2010). It has been observed that the magnitude of sensible heat fluxes can vary by a factor of up to 4 between city and countryside (Ching, 1985), and between 25% and 40% within a neighbourhood area within a city (Schmid et al., 1991). This emphasises the role that multiple changes of surface type plays in determining sensible heat flux and thus convective processes. Urban land-use thus influences the structure and organisation of thermal plumes or horizontal convective rolls that develop over the surface, meaning that the mixed layer depth varies spatially across the city.

When combined with measurements of boundary layer depth and structure, flux measurements allow a comprehensive assessment of the effect of the surface energy balance on UBL dynamics. Care must be taken in correctly interpreting the footprint of the flux observations: source area models (Schmid, 1994; Kljun et al., 2002) are often used to estimate the representative area of turbulent flux measurements, despite there being no representation of the urban canopy in model formulations to date. Most observations of both fluxes and UBL depth have been campaign-based, although results from long-term campaigns are emerging (e.g., the ACTUAL project in London, www.actual.ac.uk).

4.1.3. The storage flux

It was recognised early on in urban climate studies that understanding the storage heat flux is of paramount importance, if the urban surface energy balance is to be correctly simulated (Kramer, 1987). Various schemes have emerged to capture the effect of urban heat storage (e.g., Objective Hysteresis Model, Grimmond et al., 1991) but are hard to validate given that it is impractical to measure the storage flux directly. It is computed as a residual of a measured energy balance. The residual term is thus subject to errors due to measurement, but also in the twin assumptions (a) that there is energy balance closure, and (b) that advection is negligible up to the height of measurement (Grimmond et al., 2010). Roberts et al. (2006) compared three schemes with storage fluxes deduced from observations in Marseille. The schemes captured the main diurnal cycle and performed reasonably during the day, but the magnitude of the modelled storage flux varied by a factor of two at night between schemes. Nevertheless, the key characteristic in terms of modelling UBL response is to simulate the correct phasing of urban sensible heat fluxes with respect to sunrise and sunset, which depends directly on correctly simulating the storage heat flux.

4.1.4. The anthropogenic flux

Robust methods of modelling anthropogenic heat flux have taken some time to emerge due to the complexity of relating a physical quantity to human activities (i.e., waste heat from buildings, transport-related fuel combustion), and having sufficiently accurate data sources for those activities. Sailor (2011) gave a comprehensive review of how these fluxes are estimated, and Martilli (2007) reviewed the ways in which they are integrated into mesoscale models. Of emerging importance is being able to simulate a coupled anthropogenic flux to capture potential undesirable positive feedbacks, e.g., increasing air conditioning to combat higher temperatures leads to a greater anthropogenic heat flux.

¹ <http://www.geog.ubc.ca/urbanflux/> accessed 9th September 2013.

Krpo et al. (2010) did a numerical simulation of the impact of a coupled anthropogenic heat flux scheme on UBL structure, and found temperature differences $O(1^\circ\text{C})$ above and particularly within the urban canopy, and increased TKE in the UBL above the urban area: these results were found to be sensitive to the packing density of the buildings.

De Munck et al. (2013) found similar increases in street level temperature due to inclusion of air conditioning in a coupled mesoscale model. Larger increases were seen during night-time despite larger anthropogenic heat release occurring during the day. It was suggested that this result was due to the lower UBL depth at night, as heat is mixed through a shallower layer, causing larger temperature increases. Clearly, there is potential for an important negative feedback: if surface temperatures are warmer, the UBL can be deeper, thus creating more turbulent mixing that in turn reduces surface temperature. This effect can be seen, but is subtly dependent on how large Q_F is compared to Q_H . Bohnenstengel et al. (2014) showed that the diurnal variation of anthropogenic heat flux estimated for London varied little between winter and summer, but it had most impact on winter-time UBL structure. Given seasonally small values of Q_H in winter, the additional heat input due to Q_F was sufficient to switch UBL stability from a stable to convective layer at night, whereas its impact in summer was negligible. Another interesting effect for non-equatorial cities is that the timing of anthropogenic heat release remains approximately constant all year round, but varies with respect to onset and decay of the convective boundary layer. Given that the ratio Q_F/Q_H is important, anthropogenic heat flux seems to have most impact on UBL structure when released at times other than during the daytime convective UBL.

4.1.5. The advective flux

Little progress has been made in analysing urban micro-scale advection within the urban canopy, despite the almost universal assumption that $\Delta Q_A \approx 0$. An early study by Ching et al. (1983) highlighted that horizontal heat fluxes could dominate the vertical fluxes in areas with strong horizontal temperature gradients. Research within the vegetation canopy community has led to corrections for vertical scalar fluxes to account for horizontal advection based on analysis of the governing equations for scalar transport (Paw U et al., 2000). Attempts have been made to determine ΔQ_A experimentally for carbon dioxide (Leuning et al., 2008), where budget closure is crucially important for making accurate estimates of net ecosystem exchange. Even in porous vegetation canopies this is incredibly difficult to do, which suggests a more fruitful direction for urban research may be to use numerical simulation to assess whether assuming $\Delta Q_A \approx 0$ is valid for heat in the urban energy balance. Pigeon et al. (2007) used a combination of observations and relatively coarse resolution model simulations to conclude that horizontal heat advection dominated the vertical heat flux when a sea breeze was active in Marseille during the ESCOMPTE/UBL-CLU campaigns (Cros et al., 2004; Mestayer et al., 2005). There may be potential in computing advection and flux divergence from high resolution CFD such as LES.

Pragmatically, flux measurements are most often located at sufficient fetch downstream of a change of roughness (Roth, 2000 quoting Wieringa, 1993) to ensure that the measurement is within an equilibrium layer and thus that advection can also be assumed to be negligible. However, in real urban canopies, there are multiple changes in roughness (leading to deceleration/acceleration of horizontal flow) as well as scalar source distribution (leading to horizontal heat advection). In an idealised wind tunnel experiment Barlow et al. (2004) observed approximately 25% increase in vertical fluxes within the first 2–3 street canyons after a coincident change in roughness and scalar source. This is the adjustment zone, the length of which can be estimated using the canopy drag lengthscale L_c (Coceal and Belcher, 2004; see Section 4.2.2) and is typically between 50 and 300 m, for dense to sparse urban canopies, respectively. Where a surface contains multiple changes, so-called “surface texture” (Schmid and Bunzli, 1995), the spatially averaged turbulent flux deviates from the equilibrium flux value due to such micro-advection. Whilst comparison of modelled equilibrium fluxes with observed equilibrium fluxes is valid (e.g., Grimmond et al., 2010), the atmosphere over real urban areas will respond to both equilibrium and non-equilibrium fluxes. Hence if microscale advection within urban canopies is significant we may expect to see deviations between model predictions and observations of the UBL due to lack of representation of such sub-grid scale effects. To first order, where grid scale L is much larger than adjustment scale L_c , microscale advection may well be negligible.

4.1.6. Summary

In summary, much progress has been made in measurement and modelling of the urban surface energy balance: the effect of urban materials and morphology on Q^* and Q_H is reasonably well explored; there is less accuracy in simulating latent heat flux Q_E when compared to observations; there is some capability in modelling storage ΔQ_S and anthropogenic fluxes Q_F , which cannot be observed directly. Little progress has been made in analysing micro-scale advection, despite the almost universal assumption that $\Delta Q_A \approx 0$. An aid to interpretation of measured fluxes would be further development of source area models to include an urban canopy (Fisher et al., 2006) so that they could assist with experimental design, i.e., sites are selected based on a more quantitative assessment of the urban surface. This is particularly important as more efforts are made to relate UBL dynamics to USEB: the boundary layer has an integrated response to the patchwork of surfaces, each with distinct partitioning of turbulent heat fluxes, and so local flux measurements have a much smaller footprint than measurements spanning the UBL depth. As with all urban measurements, difficulty in obtaining permission to erect towers may lead to a compromise in site selection – improved modelling tools can help to assess how compromised the actual measurements are.

4.2. Roughness sub-layer flow

Understanding the role of the roughness sub-layer (RSL) within the UBL, despite its complexities, is crucial, as it is the interface between surface and atmosphere and is strongly influenced by human activities. Pollution exposure has been a driver for many studies to understand RSL flow, although there are increasing efforts to formulate intermediate complexity models of urban canopy flow for numerical weather prediction, or to understand the microclimate in which sustainable buildings are designed. Established assumptions about fluxes and flow in the atmospheric surface layer (such as Monin–Obukhov Similarity Theory, or MOST) have to be abandoned, yet progress over the last decade in particular is resulting in more general characteristics emerging. For a review of work on radiative exchanges within the RSL, Arnfield (2003) is particularly helpful: the following sections focus on the turbulence exchange processes that he highlighted as being crucial for successful modelling of surface energy balances for individual facets within the urban canopy.

4.2.1. General characteristics

In terms of flow within the urban RSL, Barlow and Coceal (2009) reviewed results obtained by full-scale measurements, wind tunnel modelling and numerical simulation. Due to the practical difficulties of investigating flows in real streets with traffic and pedestrians, most work was completed in the 1990s and predominantly the 2000s, especially as numerical simulation techniques improved. Barlow and Coceal (2009) synthesised two different perspectives on urban turbulence: (a) a rough wall boundary layer perspective (Raupach et al., 1991), and (b) a canopy flow perspective (Finnigan, 2000). The review also classified studies by morphology as 2-D (i.e., street canyons), 3-D (i.e., cubes) or more realistic roughness element configurations. In the same year an international workshop organised by the National Centre for Atmospheric Science (NCAS) in the UK was held at the University of Reading for which material is available online² for public consumption.

Certain broad conclusions emerged from the review and workshop:

- (1) The urban RSL may be so deep over tall buildings (posited by Rotach, 1999) or so inhomogeneous over sparse canopies (Cheng et al., 2007) that the inertial sub-layer (ISL) may not exist. As by definition the log law holds in the ISL, the wind profile would not be well defined in such cases.
- (2) It is commonly assumed that flux measurements made at around $z \sim 2H$ over moderately dense canopies lie within the ISL. In reality, RSL depth can vary between approximately $2\text{--}5H$ and should be established on a site-by-site basis. Methods to determine its depth include (a) measuring flux profiles and identifying the ISL as being where the fluxes are near constant with

² http://www.met.reading.ac.uk/urb_met/workshop/.

height (Feigenwinter et al., 1999; Grimmond et al., 2004) or (b) measuring wind profiles at multiple locations and identifying the lowest height above which profiles agree, as is often done in wind tunnel studies (Kastner-Klein and Rotach, 2004). More fundamental turbulence characteristics can be used: Roth and Oke (1993) determined that point measurements of flux were indeed in the ISL if the ratio between vertical and streamwise velocity spectral densities approached the isotropic ratio of $S_w/S_u = 4/3$ in the inertial sub-range. This is an elegant approach if only one flux measurement height is being used as this is a universal characteristic for homogeneous turbulent flow, as found in the ISL.

- (3) The overlapping shear layers at roof-top produce flow that is highly turbulent, characterised by large TKE production and TKE transport both upwards and downwards (Christen, 2005). This has implications for numerical modelling techniques assuming local balance between TKE production and dissipation, i.e., k - ε turbulence closure used in RANS models where k is TKE and ε is TKE dissipation rate.
- (4) Turbulence within urban canopies does show some characteristics similar to vegetation canopies. One common characteristic is the skewness of the gust distribution near building top: for the vertical wind component it is negatively skewed (skewness $Sk_w \approx -0.5$), and for streamwise gusts aligned with the mean flow direction it is positively skewed ($Sk_u \approx 0.5$) (e.g., Christen et al., 2007). Such intermittent, large gusts are distinctively different to flow over open country, in which the gust distribution is near Gaussian.
- (5) Turbulence length-scales become relatively small near the top of the urban canopy, despite there being relatively efficient transport of momentum (Christen, 2005; Coceal et al., 2007). This is in contrast to vegetation canopies, where in-canopy turbulence exchange is almost fully dominated by a large-scale eddy near canopy top, generated due to shear instability at the inflection point in the wind profile. This prevents a simple model of urban turbulence from being defined that is analogous to vegetation canopies (the Mixing Layer Analogy – Raupach et al., 1996).

4.2.2. Modelling urban RSL flow

In terms of progress in modelling RSL flow, there is more progress in capturing mean flow rather than turbulence properties. Models can be broadly categorised in three ways:

- (1) Urban canopy models: the drag of the urban canopy is represented in the momentum budget equations, with some assumption made about turbulence closure, in order to derive a spatially averaged mean wind profile. Resulting models capture the exponential form of the canopy wind profile (Macdonald, 2000), or the relationship of mean windspeed to canopy density (Bentham and Britter, 2003). More sophisticated parameterizations include a variation of canopy drag with height, and can be used to give more realistic canopy level winds in a mesoscale NWP model (Martilli et al., 2002). Coceal and Belcher (2004) also used a height varying drag coefficient, $c_d(z)$, to deduce a canopy drag lengthscale L_c related to morphological parameters:

$$L_c = \frac{2H}{c_d(z)} \frac{(1 - \beta)}{\lambda_f} \quad (2)$$

where β is the volume fraction occupied by buildings, and λ_f is the frontal area density. The distance taken for flow to accelerate or decelerate within a canopy after a change in roughness is approximately $3L_c$.

- (2) Empirical parameterizations: observations show that the shear stress increases throughout the depth of the canopy which is due to the form drag of buildings exerted on the flow. Rotach (2001) first conceptualized an urban shear stress profile with a peak near roof-level, and proposed an empirical form for it based on the full-scale measured data available at the time. Kastner-Klein and Rotach (2004) modified the parameterization based on a more extensive wind tunnel study of Nantes, France for which many more stress profiles could be measured. Although not generally applicable, the concept has assisted development of simple urban dispersion models.

- (3) Models based on mean flow structure: flow along street canyons can be decomposed into channelling along the street and a recirculation across it (Dobre et al., 2005). Caton et al. (2003) derived an analytical model for turbulent exchange between a street canyon and the air above based on a representation of a strong recirculation and a shear layer. Soulhac et al. (2008) derived analytical models of flow for more complex street layouts based on simply the incoming flow and the distance to wall or the ground. Such an approach has helped to justify a street network modelling approach to within-canopy dispersion (the SIRANE model, (Soulhac et al., 2011)), where pollutants are assumed to be well-mixed in each street (i.e., a box model), and there is a simple representation of flow along the streets and exchange with the air above that is related to morphology.

4.2.3. Summary

There are still unanswered questions at a fundamental level about turbulent flow in the RSL for homogeneous urban canopies such that modelling turbulent flow is not yet possible. Modelling mean flow and exchange with the air above, especially for dispersion applications, has been more successful. There has been less conclusive work on buoyancy effects on flow and heat fluxes within urban canopies. This is in part due to the difficulty in resolving or parameterizing the thermal boundary layers on building surfaces in modelling work (Cai, 2012), and the experimental challenges in observing or simulating heat transfer processes on such small scales using physical modelling (Kanda, 2005). It is important to resolve these technical issues due to the increased emphasis on accurate modelling of building temperatures in future urban climates, especially for energy system planning (e.g., Salamanca et al., 2010).

Research into the urban RSL has mostly considered homogeneous urban canopies with simple layout. Fast-growing cities can contain extensive neighbourhoods of high-rise buildings, a canopy type for which there has been little research to date. Individual tall buildings can perturb street level flow laterally due to strong downdrafts bringing faster flowing air directly down into the urban canopy (Heist et al., 2009). Flow around a group of high rise buildings (e.g., as in a Central Business District) may not resemble canopy flows at all: instead street level flow may be coupled directly to flow high above the surrounding canopy in their wakes. They may also collectively cause a large wake of long, downstream extent and in stable conditions they may trigger waves that permeate the UBL (Collier, 2006). LES may prove a useful numerical tool in stimulating such flows on which analysis can be based (e.g., Letzel et al., 2008), and remote sensing observations such as Doppler lidar (e.g., Newsom et al., 2005) can measure flow at the scale of such large buildings.

4.3. The inertial sublayer

Following the European COST 715 Action, it was identified that ISL fluxes are key in linking the neighbourhood scale climate to the overall UBL development (Fisher et al., 2006). In Section 4.1 it was assumed that fluxes are measured in the ISL, but here it is asked whether urban turbulence observations in the ISL also obey surface layer Monin Obukhov similarity theory, or MOST? This is an important question for dispersion modelling in particular, where turbulence profiles are often parametrized according to MOST and calculated in terms of friction velocity u^* , and stability parameter z/L .

4.3.1. General characteristics

The review paper by Roth (2000) still stands as an exhaustive collection and analysis of urban ISL field turbulence data. A summary of his key findings follows:

- (1) A logarithmic wind profile is demonstrated in the urban ISL under neutral conditions.
- (2) Standard deviations of the wind components (σ_u , σ_v , σ_w) in the neutral limit agree with results for rural surfaces (Counihan, 1975) within the scatter of the data, i.e., 2.50: 1.90: 1.25.
- (3) Turbulence intensity for each component in the neutral limit is higher than for a rural reference.

- (4) Spectral peak frequencies in the neutral limit for the vertical component are smaller than for a rural reference spectrum (Kaimal et al., 1972). Taken with other discrepancies for unstable and stable conditions for all wind components, Roth concludes that MO scaling does not hold for measurements at $z < 3H$, and concludes that other turbulence scales due to the roughness element spacing are playing a role.

4.3.2. Progress since Roth (2000)

Roth's review focused mainly on available data at the time for heights up to c. $6H$. Since then, various studies have used masts on top of tall towers or buildings at higher heights ($z \approx 10\text{--}20H$) and found broad agreement with locally scaled surface layer similarity relationships (Al-Jiboori et al., 2002; Wood et al., 2010). In addition to the advantage of such high level measurements in having large urban flux footprints, the towers were high enough to penetrate the mixed layer where mixed layer scaling (Willis and Deardorff, 1974) is more appropriate (see Section 4.4).

Simultaneous observation of all heights of the UBL is desirable, particularly given that complex UBL structure may exist between the surface and height of observation. Ideally, profiles of fluxes should be measured to fully understand the ISL and UBL structure. In rural areas this task is easier as tethered balloons or high instrumented towers can be used. Remote sensing techniques for direct observation of profiles of turbulent fluxes are still being developed (Emeis, 2010) but have great potential for urban areas, being far more easily deployable. Measuring full-scale flux profiles would allow the kind of insights into UBL flow which are now achievable only in wind tunnel or numerical modelling and are essential for proper theoretical development.

4.4. The mixed and residual layers

Roth (2000) noted that “the UBL has received far less attention (than surface fluxes)”, meaning the upper 90% of the UBL, consisting of the mixed layer by day or residual layer by night. This is in part due to the difficulty of observation: radiosondes and tethered balloons would normally be used to explore this region of the UBL but are hard to deploy in urban areas. In the intervening period active remote sensing technologies have developed quickly, allowing continuous and well-resolved observations of UBL flow and turbulence. The following section reviews firstly studies of UBL depth and mean profiles, then turbulence characteristics throughout the depth of the UBL by day and night.

4.4.1. UBL depth

Given the large surface sensible heat flux over urban areas it is perhaps no surprise that the day-time convective UBL is deeper than the surrounding rural boundary layer. This has been observed many times (Dupont et al., 1999; Angevine, 2003; Davies et al., 2007; Pal et al., 2012) and can now be successfully captured in model simulations with physically realistic representations of the urban surface energy balance (e.g., Piringer et al., 2007). Across all states of the UBL it is desirable to determine its depth as this determines pollution levels. Seibert et al. (2000) reviewed methods for determining mixing height with respect to modelling air pollution as part of the COST Action 710. Remote sensing techniques have developed to the point that continuous observations of boundary layer depth are becoming routine, and can be deployed alongside long-term flux measurements, allowing more effective model evaluation and improvement. There are many methods for deriving boundary layer or mixing height from remote sensing instruments (see Chapter 4 in Emeis (2010) for a comprehensive review). It is important to note that boundary layer depth as defined by an inversion height is not necessarily the same as the physical quantities sensed by the different instruments (e.g., lidars measure backscatter from aerosol particles; sodars measure backscatter from acoustic refractive index variations; both are subject to active turbulent mixing). Model formulations of boundary layer depth can be defined on inversion height in a convective boundary layer (CBL) or top of ground-based turbulent layers in a stable boundary layer (SBL). There is current work in the community to reconcile differences between observational methods and model formulations (e.g., Dandou et al., 2009; Schäfer et al., 2012), which is crucial to the design of any long-term observation networks intended for model evaluation or even data assimilation. This will be particularly important for the

UBL, which can have a complex spatial and vertical structure due to advection across a surface with strongly inhomogeneous heat flux.

4.4.2. Mean profiles

In terms of mean profiles throughout the UBL depth, radiosondes can naturally provide most meteorological variables, but cannot always be released in dense cities due to civil aviation authority restrictions, and are not continuous. Early observations of temperature profiles over New York using instrumented helicopters (Bornstein, 1968) showed weak and/or infrequent surface-based inversions, and multiple weak inversions aloft in the residual layer. In terms of remote sensing of temperature profiles, Pelliccioni et al. (2012) used a Sodar-RASS system to measure temperature and wind profiles over one year in Rome, Italy. By applying MOST to surface-based flux measurements, they tested its predictions against the measured mean profiles up to 200 m, finding it more accurate for temperature (error magnitude less than 50%) than windspeed (error up to 300% in stable conditions). All acoustic remote sensing instruments can be difficult to deploy due to their operational noise and acoustic echoes from nearby buildings. Nevertheless, datasets of temperature profiles in particular are lacking, and thus data from such systems, carefully deployed and interpreted, are very valuable.

There has been more progress on observation of wind profiles than other quantities by Dopplerized sodar or lidar. Emeis et al. (2004, 2007) and Barlow et al. (2008) used acoustic remote sensing to derive wind profiles and noted the sensitivity of the profile to underlying heterogeneous roughness. Drew et al. (2013) compared an extensive database of Doppler lidar wind profiles measured over London with various wind profile formulations used in wind engineering (i.e., power law, log law) and found best agreement for near neutral profiles with a non-equilibrium form of the wind profile (Deaves and Harris, 1978) combined with 1 km scale estimates of the roughness length, z_0 . Dual Doppler lidars (Collier et al., 2005; Newsom et al., 2005; Davies et al., 2007) can improve the accuracy of derived wind profiles and provide dense networks of “virtual towers” (Calhoun et al., 2006), which is especially useful if the urban windfield is complex.

4.4.3. Turbulence profiles

It is important to study turbulence profiles in the UBL for application to air quality modelling, pollutant dispersion, or for determination of turbulence closure schemes in mesoscale models. Roth (2000) tested mixed layer scaling for the CBL, i.e., turbulence profiles scaled using either convective velocity, w_* , or scaling temperature, θ_* , are unique functions of height, z , divided by boundary layer depth, z_i , to give scaled height z/z_i (Willis and Deardorff, 1974). This analysis revealed good agreement between Sorbjan's (1989) empirical formulations for profiles of vertical velocity variance, σ_w^2 , for a rural CBL and the scaled data, but with larger values of vertical velocity variance nearer to the urban canopy. Due to a lack of data, profiles of temperature variance, σ_T^2 , could not be definitively compared.

Wood et al. (2010) made point measurements on the 190 m BT Tower in London. They approximated z_i from the peaks of the u and v component spectra (Liu and Ohtaki, 1997) and thus tested mixed layer scaling for σ_w^2 and σ_T^2 profiles. There was good agreement between the σ_w^2 profiles and the results of Lenschow et al. (1980) with a peak at $z/z_i \sim 0.35$. This is in agreement with later Doppler lidar profiles of σ_w^2 in London taken by Barlow et al. (2011), who used the observed mixing height instead of the inversion height, which was not available. The consistency of these results agrees with earlier findings of Ching et al. (1983) who suggested that the mixing height correlated with the lengthscale of lateral turbulence, rather than the inversion height. Profiles of σ_u^2 and σ_v^2 approximated 1 throughout the depth of the CBL when scaled with w_*^2 which agrees with other rural results (Caughy and Palmer, 1979). For σ_T^2 the Wood et al. (2010) profile agreed qualitatively with the Uno et al. (1992) profile data scaled by Roth (2000), in that values of σ_T^2/θ_*^2 were higher than values observed over a rural area (Sorbjan, 1989).

Appropriate scaling of turbulence profiles over urban areas is important to determine as model parameterizations assume classical boundary layer behaviour. Taken together these results suggest that momentum transfer is indeed similar to a classical mixed layer, but heat transfer may be somewhat different, perhaps due to the heterogeneous surface heating in an urban area. This hypothesis requires further testing using full-scale observations and high quality LES modelling.

4.4.4. Cloud-topped UBL

Very little is known about the impact of clouds on UBL structure. Barlow et al. (2011) used Doppler lidar to observe turbulence structure alongside aerosol backscatter profiles in autumnal London. By day, with moderate wind and total cloud cover the σ_w^2 structure resembled other near neutral boundary layers when scaled using friction velocity u^*2 . By night, a turbulent layer below cloud base existed, distinct from a surface-based turbulent layer. Such turbulence structure beneath stratocumulus clouds is driven by cloud top cooling (Hogan et al., 2009), akin to an “upside-down CBL”. By day or night, non-precipitating, cloud-topped boundary layers in urban areas are likely to be a common class of boundary layer, albeit less “exciting” (!) due to the suppressed heating of the urban surface. Barlow et al. (2011) determined a larger diurnal range in mixing height for clear (150–850 m) compared to cloudy conditions (300–750 m) in late autumn. However the impact of enhanced shear, reduced moisture and storage of heat in the urban fabric mean that cloud-topped UBLs may have a structure distinct from their rural counterparts and are worthy of study, particularly in view of dispersion or air quality/chemical transformation of pollutants.

4.4.5. The nocturnal UBL

A single, simple conceptual picture of a nocturnal urban boundary layer does not exist. Its formation is particularly complex due to several factors:

- (a) In low wind-speeds, a positive heat flux can be maintained after the net radiation becomes negative at night due to the local urban surface energy balance, i.e., the surface cools less rapidly than the air above. This leads to a weakly convective turbulent layer that decays gradually with surface cooling, of a depth determined by the buoyancy of the surface air with respect to the ambient temperature profile. This layer can be identified with the “boundary layer urban heat island” where temperatures are elevated compared to the rural background.
- (b) In moderate to high wind-speeds, cooler rural air advects over the warmer urban surface which leads to a positive surface heat flux, but combined with wind shear. This leads to a near neutral layer of a depth determined by IBL growth in addition to the local surface energy balance. Uno et al. (1992) observed a near-neutral ground-based layer with an elevated inversion layer at night-time over Sapporo. This thermal IBL can be identified with the “thermal plume” concept, where warmer air is mixed up and advected downwind of the urban surface.
- (c) In non-flat terrain, even relatively shallow orography can trigger downslope flows and lead to cold air pooling. For cities surrounded by hills (e.g., Mexico City, Salt Lake City), strongly stable layers can form over the urban surface.
- (d) For coastal cities, sea breezes can be maintained into the night due to the UHI maintaining a positive land–sea temperature difference after sunset. Similar to case (b) above, a shallow, weakly convective layer can be maintained due to advection of colder air.
- (e) Jets can be caused due to a variety of mechanisms generally involving a surface-based inversion due to either local cooling or katabatic flow. It is suggested here that jets are formed due to mesoscale factors (e.g., stable layers forming over surrounding rural areas cause flow aloft to “decouple” from the surface), and the rougher, warmer urban surface modifies the existing jet structure through advection and turbulent mixing.

Points (c), (d), and (e) can all be classed as mesoscale flows as they are not driven locally by the urban surface itself (although it does modify them), and will be discussed in more detail in Section 4.6 below.

The depth of the nocturnal UBL is difficult to determine (Fisher et al., 2006). Due to the small scale of turbulent mixing present in the nocturnal boundary layer (NBL), spatial differences in cooling rate due to the heterogeneous layout of the urban surface can cause night-time boundary layer structure on calm nights without advection to be highly spatially variable, as turbulence and advection do not “smear out” differences. For instance, under low winds stable layers may form over extensive cool surfaces such as parks, whilst a convective layer exists over nearby buildings. Pal et al. (2012) used a mobile lidar to observe the spatio-temporal characteristics of NBL depths over Paris, finding spatial variability between 330 and 95 m across urban and sub-urban areas, and qualitative correlation with

spatial variability in UHI. Many studies have observed the difference in urban and rural NBL depths, although given the spatial variability at night-time these results are location specific.

4.4.6. Summary

In summary, it has been established that UBLs are generally deeper and less stable than rural boundary layers, and their daytime turbulent structure broadly resembles CBLs in certain, but not all, respects. Nocturnal UBLs are still not fully characterised due to the sensitivity of their structure to local variations in surface energy balance and advection of rural air over the urban surface. These results suggest there is still further work to be done in assessing spatial variability of UBLs. There has been little work on cloud-topped urban boundary layers, despite plenty of work on the effect of cities on precipitation (Shepherd, 2005). The difficulties in observing humidity structure at height over the urban surface has led to a dearth of research into UBL moisture (despite early observations during the METROMEX campaign, which had urban effects on precipitation as a motivation). Nor has there been significant focus on the morning and evening transitional boundary layer (Grant, 1997; Fernando, 2010), despite its importance in controlling air pollution concentrations during rush hour periods at the start and end of the day, or the evolution of the surface UHI. Recent developments in LES (e.g., Letzel et al., 2008) and high resolution mesoscale modelling are starting to reveal turbulence structure in the UBL never considered before and should complement experimental efforts in real cities.

4.5. Urban heterogeneity

It is often said that urban surfaces are heterogeneous but the effect on UBL structure is rarely studied in a quantitative way. In part this is due to the extreme difficulty in observing the UBL at multiple locations, or the limited domain afforded in wind tunnel or CFD simulations. Now that remote sensing technology allows improved observations of the UBL at larger scales, the effect of advection across the heterogeneous urban surface should be taken into account when interpreting profiles measured at a single location. This section reviews the scant literature available on urban heterogeneity, and proposes use of the “blending height” concept (Wieringa, 1986) to quantify urban surface heterogeneity and identify heights above which the influence of individual neighbourhoods is blended out.

4.5.1. Conceptual models for urban heterogeneity

The simplest conceptual model of atmospheric response to surface heterogeneity is the IBL (Garratt, 1990), i.e., profiles of fluxes and mean profiles adjust gradually with height downstream of a single change in surface roughness or scalar flux, often quasi-2-D, e.g., a straight coastline. Despite

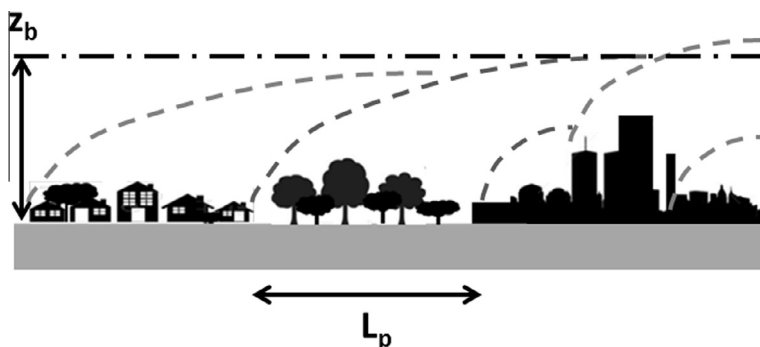


Fig. 3. Schematic diagram showing the blending height, z_b (indicated by dash-dot line), for a collection of urban neighbourhoods, as well as dominant lengthscale of heterogeneity, L_p and multiple overlapping internal boundary layers (indicated by dashed lines). The ratio z_b/L_p lies between approximately 0.03 and 0.13, and L_p lies between 500 and 5000 m in urban areas.

often being assumed, urban IBLs are little studied (Fisher et al., 2006). Cheng and Castro (2002) simulated the growth of an IBL over an array of cubes in the wind tunnel and found the growth rate with fetch to be slower when compared with classical results. Whether their result is a special case is unclear.

In a real urban area there are multiple changes of surface on a range of scales in a “patchwork”. Fig. 3 shows a conceptual picture of the atmospheric response to a collection of urban neighbourhoods. There are several “overlapping IBLs”, such that nearer the urban canopy there are spatially localised patches of flow in local equilibrium with the surface. The depth of these local IBLs depends on each patch size and is clearly spatially complex. A simplifying assumption is that a blending height z_b can be assumed above which flow is horizontally homogeneous; and that this can be related to a lengthscale of heterogeneity L_p , which represents the *dominant* patch size. A simple expression due to Wood and Mason (1991) is that $z_b = 2L_p(u_*/U)^2$ where u_*/U is defined above the blending height.

The blending height concept is also applied to assist design and interpretation of aircraft-based flux measurements over heterogeneous terrain (e.g., Bange et al., 2006, during the LITFASS campaign on surface heterogeneity) as flux measurements above the blending height are more consistent with overall boundary layer response. Note that the blending height is a lengthscale, i.e., the actual height at which a flow variable (e.g., velocity, heat flux, etc.) is homogeneous may be some multiple of the estimated blending height.

4.5.2. Quantifying urban heterogeneity and the blending height

LES has been used as a tool in investigating whether the blending height concept is correct. Bou-Zeid et al. (2004) confirmed the presence of a blending height for velocity and thus determined z_b for flow above a surface with regular heterogeneity of a single lengthscale L_p . They then applied the same methodology to a surface with irregular heterogeneity on a range of lengthscales (Bou-Zeid et al., 2007), deducing a methodology for estimation of dominant lengthscale L_p , and a relationship between L_p and z_b

$$\left(\frac{z_b}{1.7\kappa L_p + z_b}\right)^2 = \sum_{i=1}^N \left[\frac{f_i}{\left(\ln \frac{z_b}{z_{0,i}}\right)^2} \right] \quad (3)$$

where κ is von Karman's constant, f_i is the area fraction of the i th surface type (total number N) and $z_{0,i}$ is the roughness length of the i th surface type. The equation was applied by Barlow et al. (2008) to a sub-urban area in Greater Manchester, UK to assist interpretation of sodar wind profiles. The lengthscale was estimated to be $960 < L_p < 1770$ m, with corresponding blending height values calculated using Eq.(3) of $140 < z_b < 230$ m. As the maximum height of sodar measurements was 110 m, it was deduced that measured wind profiles were responding to local patches of roughness on the neighbourhood scale. Strong dependence of wind shear on wind direction was observed, which is consistent with measurements being taken in a horizontally inhomogeneous layer below the blending height.

Given this result, the question arises, how might the lengthscale of heterogeneity, and thus the blending height, vary across a city? Padhra (2010) defined L_p by using a different approach based on building morphology data for London. Values of plan area density λ_p were calculated over gridboxes of increasing length up to 5000 m until the mean value converged to a stationary statistical value, defined to be where the coefficient of variation $\sigma_{\lambda_p}/\bar{\lambda}_p < 0.0125$, where σ_{λ_p} is defined as the standard deviation of λ_p values calculated for all gridbox lengths. The lengthscale L_p varied between 400 and 4500 m and showed a significant empirical relationship with λ_p : smaller values of L_p were found in the city centre where λ_p was higher, such that $\lambda_p = -0.05 \ln(L_p)$. This makes sense for a city of a concentric type like London, where buildings are densely packed in the city centre, and more sprawling sub-urban neighbourhoods exist near the edge. This range of L_p gives values of blending height as calculated using Eq. (3) between 625 m in the sub-urban areas and 30 m in the city centre. It should be noted that the relationship between λ_p and L_p is not unique and depends on city layout.

These estimated values for blending heights can be compared with values from the LITFASS project (Beyrich et al., 2002) that explicitly focused on surface heterogeneity and boundary layer response over a rural landscape. In that study, the dominant lengthscale of heterogeneity L_p , was estimated

to be 10 km. The blending height for momentum and heat fluxes, estimated using different methods, lay between 187 and 917 m and was shown to be an underestimate in many experimental cases (Bange et al., 2006). Note that the methodology used to calculate these blending heights was not the same as Bou-Zeid et al. (2007), whose blending heights were approximately 2–5 times larger, and therefore are a conservative estimate of the influence of heterogeneity on the atmosphere. Nevertheless, it is here argued that urban heterogeneity is of a scale which has a significant impact on UBL structure (i.e., the blending height can be a significant fraction of the UBL depth) and should be taken into account.

4.5.3. Implications for measurements and modelling

Whilst there are question-marks over the exact quantitative values presented here, this analysis has implications for both measurements and modelling: (a) the interpretation of data from tall towers, remote sensing, tethered sondes or aeroplane observations capable of measurements at height above the urban surface should be done very carefully – it should be discerned whether the observations are above the blending height and thus representative of the wider urban surface; or below, and likely to lie in a complex transition layer; or in a more straightforward “local IBL” (b) In mesoscale modelling the grid box is effectively an artificially imposed lengthscale below which heterogeneity is dealt with through, e.g., a tiling scheme; and it is also heuristically assumed that the blending height equals the first model level, and thus only certain scales of heterogeneity are “permitted” (see Bohnenstengel et al., 2011 for a nice discussion of this point). It should thus be remembered when comparing measured and modelled profiles that a model profile is assumed to be in equilibrium with its local, gridbox scale “neighbourhood”, and an observed profile may well not be.

In terms of future observation networks or experimental campaigns to investigate the UBL, there is a need for measurements at multiple spatial locations where possible. Remote sensing techniques such as dual Doppler lidar (Newsom et al., 2005) are an exciting development, enabling a wider spatial area to be surveyed using only two instruments. Simultaneous flux measurement over different neighbourhood types within a city should be considered, or spatially-integrating measurement techniques such as a scintillometer (Kanda et al., 2002), to determine the spatially averaged flux to which the UBL is responding.

4.6. Mesoscale flows

Cities create surface heating, moisture and roughness anomalies on the scale of several to 100 km that can drive mesoscale circulations, e.g., the UHI can cause a thermal circulation leading to convergence and uplift over the city centre. In turn, many cities are subject to mesoscale circulations driven by proximity to the coast or lakes (sea/land breezes) or orography (mountain/valley flows) – see Fernando's review of 2010. Whether externally or locally-driven, the UBL is modified. This section reviews knowledge to date on how mesoscale circulations modify local UBL structure and evolution.

4.6.1. City-driven thermal circulations

City-driven thermal circulations are caused by the difference in surface heat flux between city centre and rural surroundings. Buoyant air rises over the city; a horizontal pressure difference arises that “sucks” rural air into the city, creating flow akin to a sea breeze; in contrast to a long, straight coastline, the roughly circular shape of the city means that flow converges, leading to uplift. If rural air is moist, convergence can lead to enhanced cloud formation, which was a motivation for the METROMEX study in St Louis (Changnon et al., 1971). The horizontal velocity associated with city circulations for St Louis was estimated by Shreffler (1978) to be 1.5 m s^{-1} from measurements on 25 m high towers and easily “washed out” as synoptically-driven windspeed increased. The velocity scale for city circulations, U , is determined by the Froude number ($Fr = U/ND$), where D is the diameter of the city and N is the Brunt–Väisälä frequency, an indicator of the static stability of the background flow (Collier, 2006). A laboratory scale model was used by Cenedese and Monti (2003) to study this dependence for an idealised city, also for the case of an urban circulation interacting with a sea breeze.

Wang (2009) used LES of an idealised city to study the spatial variability in turbulent structure of the UBL during a thermal circulation. The TKE budget was calculated for the convergence zone in the

city centre, and halfway between centre and city edge. This kind of numerical experiment reveals what is hard to determine from observations alone: that UBL depth can be suppressed away from the city centre due to outflow of warm air aloft, and that velocity variance profiles are significantly affected by advection throughout the UBL depth. One consequence of this is that whilst convective conditions over urban areas suggest a localised source area for surface fluxes, the turbulent flow aloft may well be controlled by city scale advection. Clearly, such effects determined by idealised experiments may be swamped by a superposition of processes in a real urban area, but must be born in mind when interpreting model or experimental results.

4.6.2. Sea breezes and the UBL

Many cities lie on coastlines and thus coastal UBLs must be considered in conjunction with sea breeze circulations. Sea breezes penetrating into Tokyo are particularly well-studied. Yoshikado and Kondo (1989) observed deepening of the daytime mixing height due to arrival of the sea breeze front from 600 to 1700 m. Yoshikado (1989) performed numerical simulations using a simple model that confirmed intensification of mixing at the sea breeze front, but also identified a sub-urban stagnant region further inland after passage. Kusaka et al. (2000) simulated the changing interaction between the sea breeze and UHI over 85 years of increasing urbanization between 1900 and 1985 and found that penetration inland was delayed by 2 h due to enhanced urban roughness. Lemonsu et al. (2006) used a mesoscale model to simulate cases observed during the ESCOMPTE/UBL–CLU field campaign in Marseille, 2001 (Cros et al., 2004; Mestayer et al., 2005). They determined that sea breezes, driven by a combination of topography and land–sea temperature differences, arrived in the urban area later in the day, leading to suppressed mixing as cold sea air was topped by warmer urban air. A similar result was observed by Liu and Chan (2002) in a modelling study of Hong Kong. Lo et al. (2007) used a model sensitivity study to deduce that enhanced urbanization in the Pearl River Delta area of China would enhance surface heat fluxes, causing stronger thermal circulation and allowing sea breezes to penetrate further inland.

It can be seen that whilst the UHI can enhance sea breeze circulation and later inland penetration of the sea breeze front, urban roughness can act to slow it down. Taking advantage of a network of 97 wind-speed measurements in and around New York City, Bornstein and Thompson (1981) observed weak reductions in sulphur dioxide in upwind areas with the passage of a sea breeze, and stronger increases in downwind city areas due to advection of polluted air. The head of the sea breeze can be associated with enhanced mixing, whilst in its wake a more stable layer can form. Hence, whilst sea breezes may chemically bring in cleaner air, dynamically they may cause trapping of existing pollution if stability overcomes mechanical mixing. Given the complex balance of processes, the impact of sea breezes on city cooling and air pollution is site specific and requires further research.

The effect of sea breezes on the nocturnal UBL has been observed using remote sensing in a series of studies in Italy. Casadio et al. (1996) used a Doppler sodar to observe nocturnal convective activity over Rome due to the combination of heat storage in the urban surface and cold air advection by sea breezes. Rao et al. (2002) combined Doppler sodar and Raman lidar water vapour observations to estimate water vapour flux profiles over Rome over several nights. Fluxes were positive at all heights and the water vapour skewness was negatively correlated with windspeed, both observed under the influence of sea breeze advection. This was an early example of combining remote sensing methods to give flux profiles, a methodology which should be developed for future studies of UBL structure in urban areas, particularly if advection is playing a role (see Section 4.3.2).

4.6.3. Nocturnal jets and the UBL

Nocturnal jets in relatively flat terrain are created when a surface-based inversion decouples the flow from the friction of the surface by suppression of turbulent momentum fluxes, causing maximum winds at between 100 and 500 m above the surface (Blackadar, 1957; Thorpe and Guymer, 1977). The subsequent inertial oscillation results in super-geostrophic windspeeds in the early hours of the morning at mid-latitudes. Given the need for a strong surface inversion it is unlikely that jets form over urban areas, but there is observational evidence for their presence in urban areas despite a lack of surface-based inversion. Kallistratova et al. (2009) used Doppler sodars to identify jets in summer-

time windspeed profiles at a rural site to the west of Moscow, and at an urban site. Urban jets were observed to occur later in the night, at higher heights, and be less frequent than the rural jets.

The Moscow results may be consistent with a jet formed in a widespread rural stable boundary layer advecting over the urban area, weakening due to enhanced nocturnal mixing over the urban surface. This feature was observed by Barlow et al. (2014) who showed that profiles of turbulence skewness and kurtosis in the transitional convective UBL resembled a “top-down” boundary layer, indicating that rurally-sourced jets can have a big impact on urban convective turbulence profiles in morning and evening transition periods. This has implications for modelling pollutant dispersion, and hence accurate concentrations, during morning and evening traffic rush-hour periods.

In a study in both summer and winter, Kallistratova and Kouznetsov (2011) demonstrated that winter-time jets showed a quite different behaviour. Presumably due to the intense cold of the northern region causing more persistent ground-based inversions, rural winter-time jets showed less of a diurnal cycle. In very cold periods no jets were observed in the urban area, instead a convective layer was observed. Such convection may be due to increased anthropogenic heat flux in winter time in the urban area, as seen in the modelling study of Bohnenstengel et al. (2014). Nocturnal jets have also been observed in Oklahoma City (Klein and Clark, 2007) where the Great Plains Low Level Jet is a widespread feature due in part to heating and cooling of the sloping terrain (Holton, 1967).

4.6.4. Cities in complex terrain

Cities are often located in complex terrain, particularly basins or valleys between hills. The Urban 2000 experiment (Allwine et al., 2002) was conducted in October 2000 in Salt Lake City, US, and had the aim of measuring and modelling UBL structure and dispersion at night-time as influenced by orographic and lake-driven flows. Mesoscale flows across the entire valley basin were studied as part of the larger Vertical Transport and Mixing Experiment (VTMX, Doran et al., 2002). Thermally induced flows were often established at night due to downslope flows, alongside a basin-wise Low Level Jet (LLJ). Tracer dispersion in the urban areas was poor when the local downslope flows dominated, and better when the LLJ dominated, as it transported pollutants out of the valley (Darby et al., 2006).

The Phoenix Evening Transition Flow Experiment (Transflex, Fernando et al., 2013) aimed to characterise the onset of the nocturnal UBL in particular, due to the difficulty in predicting air quality at such times. The results, using a combination of remote sensing and modelling, showed a complicated series of cold, dense microfronts arriving in the urban area, causing turbulent mixing that enhanced pollutant concentrations. Kolev et al. (2000), Piringer (2001) and Coulter et al. (2004) all used remote sensing methods to observe multiple elevated layers above urban areas in complex terrain. This kind of structure is consistent with density current-type downslope flows from multiple directions. Whilst there has been a focus on the night-time UBL, Miao et al. (2009) performed a numerical study of the daytime UBL over Beijing, showing that it is dominated by mountain–valley flows that are modified by the urban surface. Sensitivity testing showed that the presence of the urban surface changed the structure of horizontal convective rolls by increasing the shear and heating at low levels.

4.6.5. Summary

Overall, research has shown that for cities in anything other than flat, homogeneous terrain, the local urban surface only modifies the UBL structure and evolution, it does not fully determine it. Hence any studies must include both modelling and measurements at the mesoscale to fully capture the driving phenomena and for correct interpretation of measurements at a single point. Observationally, this is challenging due to the spatial dependence and scale of the flow features and demands creative development of new observational techniques. Horizontally scanning radar, such as is routinely used in the weather radar network in many countries, can be used to derive larger scale, horizontally extensive flow fields due to insect transport in the boundary layer (Rennie et al., 2010) and has shown some skill in improving forecast windfields in a high resolution mesoscale model simulation of a CBL (Rennie et al., 2011). Dual polarization radars can be used to derive atmospheric refractivity from which humidity fields can be derived, e.g., passage of sea breezes. Such observations are now being developed for the UK operational rain radar network (Nicol et al., 2014) and have the potential to provide spatially extensive measurements of urban humidity, which would be an exciting and overdue development.

5. Conclusions

Progress in understanding the urban boundary layer (UBL) has been reviewed and specific conclusions regarding research priorities were drawn at the end of each section. Much progress has been achieved across a collaborative and growing community, particularly in developing methodologies for modelling and observing the UBL.

A framework was presented that treats the UBL as the superposition of many layers and characteristics seen in other classes of boundary layer – roughness sub-layer, inertial sub-layer, mixed and residual layers. Spatially, heterogeneity at the neighbourhood and mesoscale plays an important role in determining UBL vertical structure and the “blending height” concept was described. Temporally, the urban surface energy balance and mesoscale flows provide, respectively, “bottom up” and “top down” control on the fluxes driving UBL evolution. It is here suggested that the *combination* of urban surface properties is unique (i.e., energy balance, roughness sub-layer, spatial heterogeneity) but that the urban boundary layer emerges in response to them, rather than necessarily being in a unique class of its own. Whilst it is practical to still refer to an “urban” boundary layer, progress in understanding its complexities lies in borrowing from more general boundary layer studies.

Theoretical progress in understanding the UBL has already been achieved by comparison with classical results for so-called “rural” boundary layers that are homogeneous, equilibrium and stationary flows. Modelling and observational tools are now well-developed enough to start systematically exploring UBL flows as being heterogeneous, non-equilibrium and non-stationary, with the aim of developing simple models of complex processes leading to effective operational tools. As societal needs press us towards quick answers concerning sustainable and healthy urban design, the fundamental, theoretical understanding of UBL flows should not be overlooked.

Acknowledgements

The author thanks the International Association for Urban Climate for the opportunity to give a plenary talk at the 8th ICUC conference in 2012, from which this paper was developed. Colleagues are thanked for helpful discussion about urban boundary layers, particularly John Finnigan, Ian Harman, Alan Grant, Peter Clark and Stephen Belcher. Financial support for current projects feeding into the review is acknowledged, in particular EPSRC Grant Number EP/G029938/1 for the Advanced Climate Technology Urban Atmospheric Laboratory (www.actual.ac.uk) and NERC Grant Number NE/H00324X/1 for the Clean Air for London (Clearflo) Project (www.clearflo.ac.uk). This paper is dedicated to John Barlow, who taught me how to learn.

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